AD-A195 440 CONTAMINATION AND DISTORTION OF STEADY FLOW FIELD INDUCED BY DISCRETE FRE..(U) TENNESSEE UNIV SPACE INST TULLAHOMA M KUROSAKA APR 88 AFOSR-TR-88-0640 1/1

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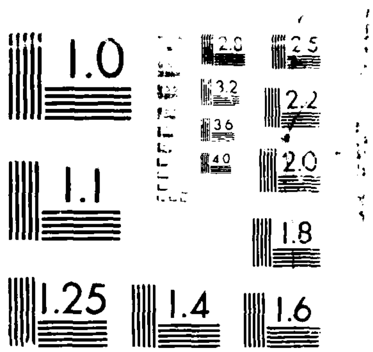
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The main objective of the program was to acquire fundamental understanding of two aerodynamic effects induced by vortices shed by blades of aircraft gas turbines: (a) the instantaneous separation of total temperature and pressure around vortices in the wake shed and its time averaged effect; and (b) the issue of over 100% efficiency measured near the hub section of an advanced turbofan design of the Air Force Aeropropulsion laboratory. Through the combination of experimental and theoretical investigations, the mechanisms of the two phenomena have been identified.

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FINAL TECHNICAL REPORT FOR A GRANT, AFOSR-83-0049

(1) TITLE

CONTAMINATION AND DISTORTION OF STEADY FLOW FIELD INDUCED BY DISCRETE FREQUENCY DISTURBANCES IN AIRCRAFT GAS TURBINES

(2) DURATION

January 1, 1983 to December 31, 1987

(3) RESEARCH OBJECTIVES

To acquire fundamental understanding of two aerothermodynamic effects induced by vortices present in aircraft gas turbines: (a) the instantaneous separation of total temperature and pressure around vortices in the wake shed by the blades and its time-averaged effect (the Eckert-Weise effect) and (b) the issue of the over - 100% efficiency measured locally near the hub section of advanced turbofans.

(4) STATEMENT OF PROBLEMS

(A) The Separation of Total Temperature and Pressure in the Wake

When a body is placed in a cross flow, the total temperature in its wake can become substantially less than the incoming one, as manifested by the fact that the recovery factor on its rearmost surface takes negative values at high subsonic flow: this is the phenomenon known as the Eckert-Weise effect.

Although a vortex street shed by the body has been a suspected cause, the issue of whether this is so and what the mechanism is, has remained unsettled. If the vortex street is indeed the cause, then from the recently established fact that the compressor blades shed the vortex street, this spontaneous decrease of the total temperature in the wake has significant influence upon the aerothermodynamics of the aircraft gas turbines. This is because the total temperature is, needless to say, an important parameter directly related to the performance of aircraft engines. In addition, the effect has implications related to the cooling problem of high-temperature turbines.

(B) Over - 100% Efficiency Issue in Advanced Turbofan

This problem is motivated by the following experimentally observed oddity found in an advanced turbofan, the Hi-Thru Flow Compressor designed by the Air Force Aeropropulsion Laboratory: *the local adiabatic efficiency measured in the first fan stage was* discovered to exceed 100% near the hub, although near the tip, it was around 75%. If and when the adiabatic efficiency exceeds 100%, this implies that the local entropy downstream of the rotor is less than that of the upstream. Except for the smaller region close to the

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hub, the entropy change elsewhere is positive. Hence, the presence of the local negative entropy change does not violate the second law of thermodynamics. However, since the possibility of the heat transfer from the fluid to the rotor blades does not appear to account for this oddity, the existence of the negative entropy spots in the absence of heat transfer becomes a source of heat puzzlement. The examination of this issue is the subject of the objective (B).

(5) RESULTS

(A) In this investigation on the Eckert–Weise effect (published as Pub. 1), we first examined the cause of the Eckert–Weise effect by enhancing the vortex shedding through acoustic synchronization: resonance between the vortex shedding and transversely standing acoustic waves in a wind tunnel. At the lower synchronization, where a ringing sound emanates from the wind tunnel, the recovery factor R at the rearmost section of the cylinder is found to become negative even at a Mach number of 0.2; the base pressure (C_{pb}) takes dips correspondingly, indicative of the intensification of the vortex street. At this lowest acoustic resonance, the decrease of R and C_{pb}, uniform along the span, agrees with the expectation based on the spanwise uniformity of the lowest standing wave. At the next acoustic resonance where the standing wave now varies along the span, the corresponding dips in R and C_{pb}, non-uniform along the span, reveals an interesting 'strip-theory'-like behavior of the vortex intensities in the vortex street. These results correlating the change in R with C_{pb} confirm that the Eckert–Weise effect is indeed caused by the vortex shedding, the mechanism of which was examined theoretically next.

A simple theoretical argument, bolstered by a full numerical simulation, showed that the time-varying static pressure field due to the vortex movement separates the instantaneous total temperature into hot and cold spots located around vortices; once time-averaged, however, the total temperature distribution conceals the presence of hot spots and takes the guise of a colder wake, the Eckert–Weise effect. Therefore, the correct explanation of the Eckert–Weise effect, a time-averaged phenomenon, emerges only out of, and only as a superposition of, instantaneous total temperature separation around vortices. Such a separation is not confined to the outside of vortex cores; every vortex in its entirety becomes thermally separated. Nor is it limited to the far downstream equilibrium configuration of the Kármán vortex street but applies to the important near-wake vortices, and to any three-dimensional vortical structure as well. For low subsonic flows in particular, this dynamical explanation also leads to a similar separation of total pressure; these features may thus be potentially exploited as a general marker to identify and quantify vortices.

These instantaneous separations of total temperature and pressure were confirmed by the time-accurate measurements carried out in collaboration with Prof. Ng of Virginia Polytechnic Institute and State University (Pub. 2.). The data were obtained by placing behind the cylinder a high-frequency response probe, an aspirating probe. Not only are

these time traces taken in the near-wake qualitatively similar, but also qualitatively they agree with predictions of Pub. 1.

In Pub. 3, an expanded discussion of them are presented

Beside the above, two additional subjects arose from these were reported as by products: (a) several illustrative examples of illusory appearance of streaklines around unsteady vortices are pointed out in Pub. 4 and (b) the prospect of negative heat transfer in separated flows are discussed in Pub. 5.

(B) To resolve the issue of over - 100% efficiency, a cylinder embedded in a sheared velocity profile was used as a simple model to simulate the rotating compressor blade (Pub. 6). By using variously instrumented cylinders, negative entropy changes were found in the leeside of the cylinder representing the downstream hub section of the compressor blade. By following trace gases, it was found that there existed a spanwise transport next to the cylinder on the leeside, and that this transport was due to the kármán vortices shed from the cylinder.

The results show that the simple model of a cylinder in a sheared flow simulates the compressor blade very well. Analysis of experimental data shows that there exists a pressure gradient on the leeside of the cylinder which drives a spanwise flow. This, in turn, creates a region of negative entropy changes in the area of the cylinder corresponding to the hub region of the AFAPL compressor blade, which is now found to be due solely to the spanwise transport of energy.

In the course of this part of the investigation, it was found (Pub. 7) that even for a uniform incoming flow, vortices induce a strong cross-current, flowing along the span of the cylinder from the side-walls to the center of the tunnel. The mechanism for this is traced to the one similar to the one updraft induced by a tornado near the ground.

(6) PUBLICATIONS

1. Kurosaka, M., Gertz, J. B., Graham, J. E., Goodman, J. R., Sundaram, P., Riner, W. C., Kuroda, H. and Hankey, W. L., "Energy Separation in a Vortex Street," *Journal of Fluid Mechanics*, vol. 178, pp. 1-29, 1987.

2. Ng, W. F., Chakroun, W. M., Kurosaka, M., "Energy Separation in a Vortex Street (II): Time-Resolved Measurements of Total Temperature and Pressure," submitted for publication to the *Journal of Fluid Mechanics.*

3. Sundaram, P., Kurosaka, M. and Wu, J. M., "Vortex Dynamics Analysis for the Kinematics of Unsteady Vortex Wakes," to be presented at the First National Fluid Dynamics Congress, Cincinnati, Ohio, July 24-28, 1988.

4. Kurosaka, M. and Sundaram, P., "Illustrative Examples of Streaklines in Unsteady Vortices: Interpretational Difficulties Revisited," *Physics of Fluids*, vol. 29, No. 10, pp. 3474–3477, 1986.

5. Kurosaka, M., Graham, J. E. and Shang, J. S., "Negative Heat Transfer in Separated Flows," submitted for publication to the *International Journal of Heat and Mass Transfer*.

6. Kurosaka, M., Marble, F. E., Goodman, J. R., Wohlman, R. A. and Tirres, L., "Negative Entropy Change Created Within a Flow," to be submitted for publication to the *Journal of Fluid Mechanics*.

7. Kurosaka, M., Christiansen, W. H., Goodman, J. R., Tirres, L. and Wohlman, R. A., "Cross-Flow Transport Induced by Vortices," submitted to *AIAA Journal* for publication.

(7) THESES WRITTEN UNDER THE GRANT

- Riner, W. C., "Enhancement of Temperature Drop Behind Cylinders by Acoustic Synchronization," M.S. Thesis, August 1985, The University of Tennessee, Knoxville, TN.
- Dang, Khanh, "The Effect of Viscosity Upon an Unsteady Vortex," M.S. Thesis, August 1986, The University of Tennessee, Knoxville, TN.
- Sundaram, P., "Studies on Unsteady Vortex Motion Including Thermo–Fluid Interactions," Ph.D. Thesis, March 1987, The University of Tennessee, Knoxville, TN.
- Wohlman, R. A., " The Generation of Negative Entropy Changes in the Wake of a Cylinder Embedded in a Sheared Velocity Flow," M.S. Thesis, March 1988, The University of Tennessee, Knoxville, TN.
- Tirres, L., "A Study of Flows Behind Bluff Bodies Immersed in a Sheared Flow," M.S. Thesis, March 1988, The University of Tennessee, Knoxville, TN.

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